Borehole Induction Logging for the Dynamic Underground Stripping Project LLNL Gasoline Spill Site

Contents

Borehole Induction Logging for the Dynamic Underground Stripping Project LLNL Gasoline Spill Site

S. Boyd, R. Newmark, and M. Wilt

Abstract

Borehole induction logs were acquired for the purpose of characterizing subsurface physical properties and monitoring steam clean up activities at the Lawrence Livermore National Laboratory. This work was part of the Dynamic Underground Stripping Project's demonstrated clean up of a gasoline spill. The site is composed of unconsolidated clays, sands and gravels which contain gasoline both above and below the water table. Induction logs were used to characterize lithology, to provide "ground truth" resistivity values for electrical resistance tomography (ERT), and to monitor the movement of an underground steam plume used to heat the soil and drive volatile organic compounds (VOCs) to the extraction wells.

Induction logs collected before steaming show close correlation with lithology and are useful for identifying the more permeable zones. The sands and gravels are easily identified by a relatively high resistivity as compared to the silts and clays. During the steam injection phase, subsurface temperatures were monitored and induction logs were obtained periodically. The resistivity decreases throughout the heated zone. Subsurface resistivities typically dropped by a factor of two or more as the subsurface temperature increased to more than 100 degrees C. Contour plots of the induction data from several of the monitoring wells also indicate regions and depths of low resistivities

corresponding with the steam saturated gravels. In the fine-grained silts and clays, the decrease in resistivity is primarily a result of temperature effects; in the coarser-grained sediments, both the fluid saturation and chemistry change as well as the temperature, resulting in lower resistivities (Newmark and Wilt, 1992).

Introduction

Induction logging has long been used in the petroleum industry for formation evaluation prior to well completion activities. The logs are primarily sensitive to the rock pore fluids and are therefore used to distinguish petroleum bearing intervals from fresh and saline water zones. Together with other logs they may be used to distinguish coarse sediments from fines and to correlate various horizons for geological interpretation. Due to the dependence of resistivity on pore fluid type, temperature, and salinity, these logs are also very useful for monitoring remedial activities associated with the clean up of subsurface contaminants. This is particularly true if these activities involve the injection of a secondary agent such as steam or solvents.

Lawrence Livermore National Laboratory (LLNL) and the University of California, Berkeley, College of Engineering, have developed a suite of remediation techniques to clean up subsurface contamination. Known as Dynamic Underground Stripping[1], the method incorporates steam injection, vacuum extraction, and electrical heating for removal of subsurface contamination. The process is monitored using tomographic techniques and repeated borehole logging measurements (Newmark et al., 1992, 1994; Ramirez et al., 1994). Dynamic Underground Stripping dramatically speeds up the process of contaminant removal and thus requires real-time monitoring to identify the areal and vertical extents of the remediation and to control the process.

The Dynamic Underground Stripping technology was initially applied to a "clean site" where a number of techniques were tested in order to establish the most appropriate and cost effective methods for monitoring the removal of VOCs from the soil (Newmark et al., 1992). Of the various imaging techniques tested, electrical resistance tomography (ERT) proved to be superior in providing near real-time imaging of the steam movement between the wells. Of the various

---

[1] Patent pending

geophysical well logging methods, temperature and induction logs proved to be most useful for monitoring steam movement and providing vertical detail of the physical changes resulting from it.

Beginning in November 1992 these techniques were applied to the Gasoline Spill Site, a LLNL site contaminated with approximately 64,000 liters (17,000 gallons) of gasoline distributed both above and below the water table. Steam and electrical heating were applied to each of these zones separately to remove the gasoline (Newmark et al., 1994).

Local Geology

The Gasoline Spill Site was the location of the Livermore Naval Air Station gasoline station when the U. S. Navy occupied the present day LLNL site. During operations it was estimated that as much as 64,000 liters (17,000 gallons) of gasoline had leaked from underground storage vessels into the ground (Dresen et al., 1986). Subsequent fluctuations in the water table led to the trapping of gasoline as much as 8 m below the water table. At the start of the demonstration, gasoline was present both above and below the water table.

The near surface local geology (upper 50 m) consists of a sequence of unconsolidated gravels, sands, silts and clays of the Pleistocene Upper Livermore formation and younger Holocene rocks. The proportions are approximately 60 percent fine grained and 40 percent coarse grained sediments. The rocks were deposited by northwest flowing streams, and units are interfingered in complex ways. With few exceptions individual units in the upper 30 m are discontinuous and may not be correlated for more than a few tens of meters at most (Dresen et al., 1986; Bishop et al., 1992). The basal (38-42 m) gravel units of the Livermore formation, however, are continuous throughout the field and dip gently to the southeast.

The induction logs show an excellent correlation between coarse grained sediments and high resistivity and fined grained formations and low resistivity, (see Figure 1). Sands and gravel are typically 12-20 Ω-m or more in resistivity; the finer grained silts and clays are typically 5-10 Ω-m. There is poor spatial correlation of the rock units in the shallow part of the section. The high resistivity gravel between 35 and 40 m is evident, however, in all of the wells. This lower unit has a high permeability and is the primary steam pathway in the lower steam zone. The induction logs do not provide a clear indication of the water table about 31 m; this is because the formation's electrical conductivity has a large component due to double layer conductance associated with clays. This is typical of induction logs in more arid regions such as the western United States (Newmark and Wilt, 1992).

Induction Logging

Induction logs were acquired using a Geonics model EM-39 probe containing a dipole transmitter with an operating frequency of 39.2 kHz, a dipole receiver located 50 cm away and a focusing coil to minimize borehole effects. All of the electronics are housed in a 3.6 cm diameter probe allowing it to easily fit into the slim (5 cm) monitoring wells. The logger features a motorized winch, equipped with 200 m of cable, mounted on a small, lightweight trailer, making it easy to move by hand throughout the site. The small footprint and ease of transport was extremely useful due to the high density of equipment, pipes, wellheads and buildings that limited well access.

The induction probe measures the electrical conductivity of the formation within a zone from 20 to 100 cm from the borehole and is most sensitive to material located a distance 30 cm away. However, the sensitivity to material located within 5 cm of the borehole axis is essentially zero, making the borehole fluid negligible. The device measures the resistivity continuously as the probe is raised from the bottom to the top of the well; the device therefore has an excellent ability to distinguish individual rock units adjacent to the borehole. At this site, the wells were dry, and the determination of the absolute resistivity was typically less important than the correlation of the logs with the lithology.

The monitoring boreholes were completed to facilitate multiple uses. Wells were typically drilled to a depth of 48 m and completed with 5 cm diameter fiberglass casing fitted with ten steel electrodes for use in ERT measurements and four fixed thermocouples for temperature measurements. This multiple use provided important "ground truth" resistivity and temperature data, but it also resulted in a number of sections of poor data quality in the induction logs, due to the presence of the steel electrodes spaced at about 3 m intervals.

Induction logs were collected periodically in these boreholes beginning in February 1992 and continuing until July 1993. Each well was logged four to five times, and each log required about thirty to forty minutes. The entire site could be logged in a day. Logging measurements are generally repeatable to within five percent. On the rare occasion that the data could not be repeated to within 10 percent, and the data were discarded.

Results

Although the induction logs are useful in identifying lithologic (and permeability) variations, their primary purpose in this application was to monitor changes in the field as the steam flood progressed. These data could then be used to establish "ground truth" for ERT measurements and to calculate fluid saturation within the swept intervals.

In Figures 3, 4 and 5 we show a sequence of induction and temperature logs acquired before, during and after the steaming cycles in wells TEP 005, 009 and 003, respectively (see Figure 2). The November 4, 1992 resistivity data, depicted as solid lines, represent our baseline profiles prior to remediation. The first steam cycle began on February 4, 1993 and continued until March 12, 1993. During this time, steam was injected into two permeable zones, centered at about 25 and 35 m. Temperature and induction data collected on February 24, 1993 are depicted in the figures as dashed lines. The second steaming cycle started on June 2, 1993, and steaming of both zones continued until June 30, 1993. Induction and temperature data collected after the second steaming cycle on July 19, 1993, are depicted as dotted lines.

The logs change over time and the decrease in resistivity generally correlates with the temperature increases. For example, in Figure 3, the induction logs overlay at the top and bottom of the well and tend to separate somewhere in the middle. The first repeat induction log (February 24, 1993) indicates no change to 33m when compared to the baseline log. However, there is a substantial decrease through the zone extending from 33 to 37 m, which corresponds to a temperature increase to near steam temperature in the lower steam zone. Below 37 m the induction logs overlay once again, indicating that the resistivity changes are confined to the lower gravel by the surrounding clay beds; this is supported by the temperature log which shows ambient conditions below 37 m.

Comparing the data acquired after the second steaming cycle (July 19, 1993), with the previous data, it is apparent from the broad interval exhibiting changes that the steam permeated the entire section between the two steam zones. The induction log shows a 50 percent decrease throughout the interval except in the highest permeability aquifers of the lower steam zone (35-37 m) where it increased. The corresponding temperature log indicates a rapid decrease in this zone, a result of recharge of groundwater into the steamed zone.

Similar results can be seen in Figures 4 and 5 which show data from two other wells, TEP 009 and TEP 003, respectively. TEP 009, situated inside the ring of injection wells, lies in the path steam travels from two nearby injection wells towards the three extraction wells, and this is reflected in the log responses. The first repeat induction log (2/24/93) exhibits decreases in resistivity over a longer depth interval, suggesting greater steam coverage during the first steam cycle than that seen in TEP 005 located outside the injection ring. Increased communication between the upper and lower steam zones is a likely reason for this. The after-steaming resistivity data show an even greater region influenced by the steam injection process, and likewise feature an elevation in resistivity opposite the recharge zone between 37 and 40 m. In Figure 5 the February 24 temperature log is similar to the February temperature profile seen in TEP 005, in that the steam is detected in only one of the steam zones; in this case, it is restricted to the upper steam zone. However, the corresponding resistivity log does not reflect a localized zone of change, which may indicate poor data quality.

Discussion

The induction logs show that the electrical resistivity decreases throughout the heated zones. Steam injection can produce the following effects: 1) pore fluid heating which would decrease fluid resistivity, 2) pore water displacement which would increase resistivity, and 3) pore fluid heating which should increase clay conductance. Another aspect which might affect the resistivity is changes in pore water chemistry resulting from salinity differences between the groundwater and the steam condensate (Newmark and Wilt, 1992). Previous work by Newmark and Wilt (1992) and Ramirez and others (1993) suggests that the resistivity decreases are due primarily to the large temperature increases, and to a lesser extent to changes in fluid saturation or fluid conductance. Due to the abundance of clay minerals at the site, a significant proportion of the total electrical conductance is contributed by the double layer associated with the clays. Ramirez and others (1994) fit the observed changes in electrical resistivities during steam injection at this site using a model that accounts for the electrical conductivity from the clay double layers.

Contouring the resistivity changes observed at specific horizons leads to plan views of the effects of steam injection. For each horizon, the average resistivity difference within ± 2.5 m depth in each borehole is contoured. Figure 7 displays map views of the resistivity changes observed in ten boreholes in each of the two steam zones during the first phase of steam injection (these diagrams represent changes which occurred between February 24, 1993 and the baseline data obtained November 4, 1992.) By February 24, the steam had been injected into all six upper steam zone injectors for only a few days. The site response at about 25 m depth suggests a localized hot spot in the vicinity of the central extraction wells. In the upper steam zone, steam movement may be limited to a small region of interconnected high-permeability deposits (Noyes et al., 1993). At about 35 m depth, the lower steam zone consists of a high-permeability, sheet-like deposit of relatively homogenous, braided stream deposits which are well-interconnected hydraulically (Noyes et al., 1993). By February 24, 1993, steam breakthrough to the extraction wells had occurred, and injection rates into the lower steam zone had been decreased. Here the region of greatest change has expanded out from the center of the site in a northerly direction, as anticipated by previous hydraulic testing (Noyes et al., 1993). The evolving patterns at depth crudely reflect the inhomogeneity of the subsurface.

One of the primary purposes for using induction logs was to verify the magnitude of the resistivity changes at individual boreholes, and thus to establish a "ground truth" for the crosshole ERT resistivity images. In Figure 8 we show induction log resistivity changes together with ERT images for cross-section A-A' (see Figure 2). Soon after the onset of steaming, the ERT images could detect resistivity changes between the wells; at this time the induction logs showed no change because the steam front had not yet propagated to the monitoring boreholes. However, at later times the two cross-sections provide similar information; the logs agree quite well with the crosshole resistivity results. While the crosshole resistivity plots offer good internal coverage between the wells, they lack the detailed near-borehole information provided by the induction logs.

Conclusions

In this short paper we have demonstrated the utility of borehole induction logging during subsurface thermal remediation activities. The logs are useful in understanding the subsurface geology before remedial operations begin and are helpful in predicting which units steam will penetrate. Once the clean up is underway, the induction logs provide an independent measure of the changes in formation electrical properties near the borehole in great vertical detail. They reveal the progress of steam movement on a vertical scale comparable to the individual lithologic units. When electrical tomographic imaging techniques are utilized, the induction logs are helpful in establishing a "ground truth" near the borehole, but if no other monitoring is undertaken, then the induction logs can be used to "observe" the progress of the thermal fronts at individual monitoring locations.

Acknowledgments

This work was funded by the Office of Technology Development of the United States Department of Energy, EM-55. Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

References

Bishop, D., D. Rice and S. Nelson, (Eds.), 1992, Characterization Report, Dynamic Underground Stripping Project Clean Site Interim Engineering Report, *LLNL UCRL-AR-108707.*

Dresen, M.D., F. Hoffman and S. Lovejoy, 1986, Subsurface Distribution of Hydrocarbons in the Building 403 Area at LLNL, Lawrence Livermore National Laboratory, Livermore, California, (*UCID-20787*).

Newmark, R., R. Aines, W. McConachie, K. Udell, D. Rice, A. Ramirez, W. Siegel, M. Buettner, W. Daily, P. Krauter, E. Folsom, A. Boegel and D. Bishop, 1992, *Dynamic Underground Stripping Demonstration Project, Interim Engineering Report 1992,* Lawrence Livermore National Laboratory, Livermore, California, *UCRL-ID-110064.*

Newmark, R. and M. Wilt, 1992, Changes in Formation Electrical Properties During Steam Flood, *62nd Ann. Internt. Mtg., Soc. Expl. Geophys., Expanded Abstracts,* 488-491.

Newmark, R., S. Boyd, W. Daily, R. Goldman, R. Hunter, D. Kayes, K. Keneally, A. Ramirez, K. Udell and M. Wilt, 1994, Using Geophysical Imaging Methods to Control In Situ Thermal Remediation, *Dynamic Underground Stripping Gasoline Spill Site Report,* Lawrence Livermore National Laboratory, Livermore, California (in press).

Noyes, C., and J. Iovenitti, 1993, Pre-DUSDP Gasoline Spill Area Hydrogeologic Characterization Draft, *Dynamic Underground Stripping Gasoline Spill Site Report,* Lawrence Livermore National Laboratory, Livermore, California (in press).

Ramirez, A., W. Daily, D. LaBrecque, E. Owen and D. Chesnut, 1993, Monitoring an Underground Steam Injection Process Using Electrical Resistance Tomography, *Water Resources Research,* V. 29, No. 1, 73-87.

Ramirez, A., J. Beatty, J. Carbino, W. Daily and R. Newmark, 1994, Monitoring Thermal Treatment Processes Using Electrical Resistance Tomography, *Dynamic Underground Stripping Gasoline Spill Site Report,* Lawrence Livermore National Laboratory, Livermore, California (in press).

List of Figures

Figure 1. Correlation of resistivity and lithologic logs at the Gasoline Spill Site. Resistivities between 12-20 Ω-m correspond to sands and gravels; values between 5-10 Ω-m correspond to clays and silts. The two steam zones are identified by the higher resistivities at depths from 25-30 m and 35-40 m. In between are interbedded sands and clays.

Figure 2. Base map for the LLNL Gasoline Spill Site. A-A' denotes a cross-section through monitoring wells TEP 003, 009 and 005.

Figure 3. Comparison of lithology, induction logs and temperature logs for monitoring well TEP 005. The solid curve is the November 4, 1992 baseline resistivity. The dashed induction and temperature logs were acquired during the first steam cycle on February 24, 1993. The dotted induction and temperature logs were acquired after the second steam cycle on July 19, 1993. Electrical resistivity decreases with elevated temperatures.

Figure 4. Comparison of lithology, induction logs and temperature logs for well TEP 009. Curve patterns are the same as for Figure 3.

Figure 5. Comparison of lithology, induction logs and temperature logs for well TEP 003. Curve patterns are the same as for Figure 3.

Figure 6. Map view of resistivity changes measured in ten boreholes in the vicinity of the upper and lower steam zones, at depths of 25 and 35 m respectively, below the surface. These changes occurred between February 24, 1993 and the baseline data taken November 4, 1992. At 25 m, the steam zone appears to be limited to a small region of interconnected higher-permeability deposits in the upper steam zone. At 35 m the lower steam zone displays the greatest decrease in resistivity in a north-south direction.

Figure 7. Induction log resistivity changes shown together with ERT images. The logs agree well with the crosshole resistivity results. While the crosshole resistivity images offer good internal coverage between the wells, they lack the detailed near-borehole information provided by the induction logs.

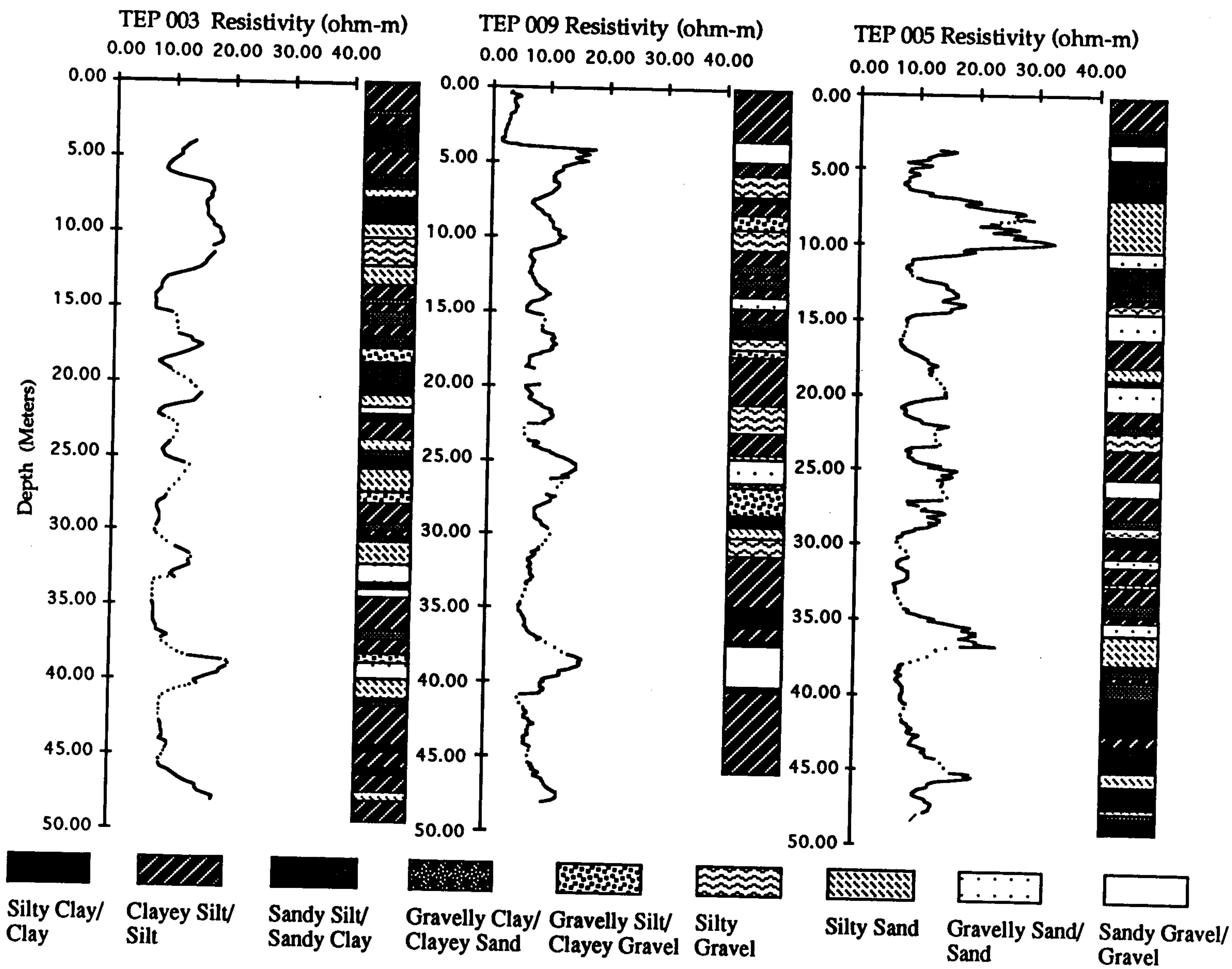

Figure 1. Correlation of lithology and induction logs at the LLNL Gasoline Spill Site.

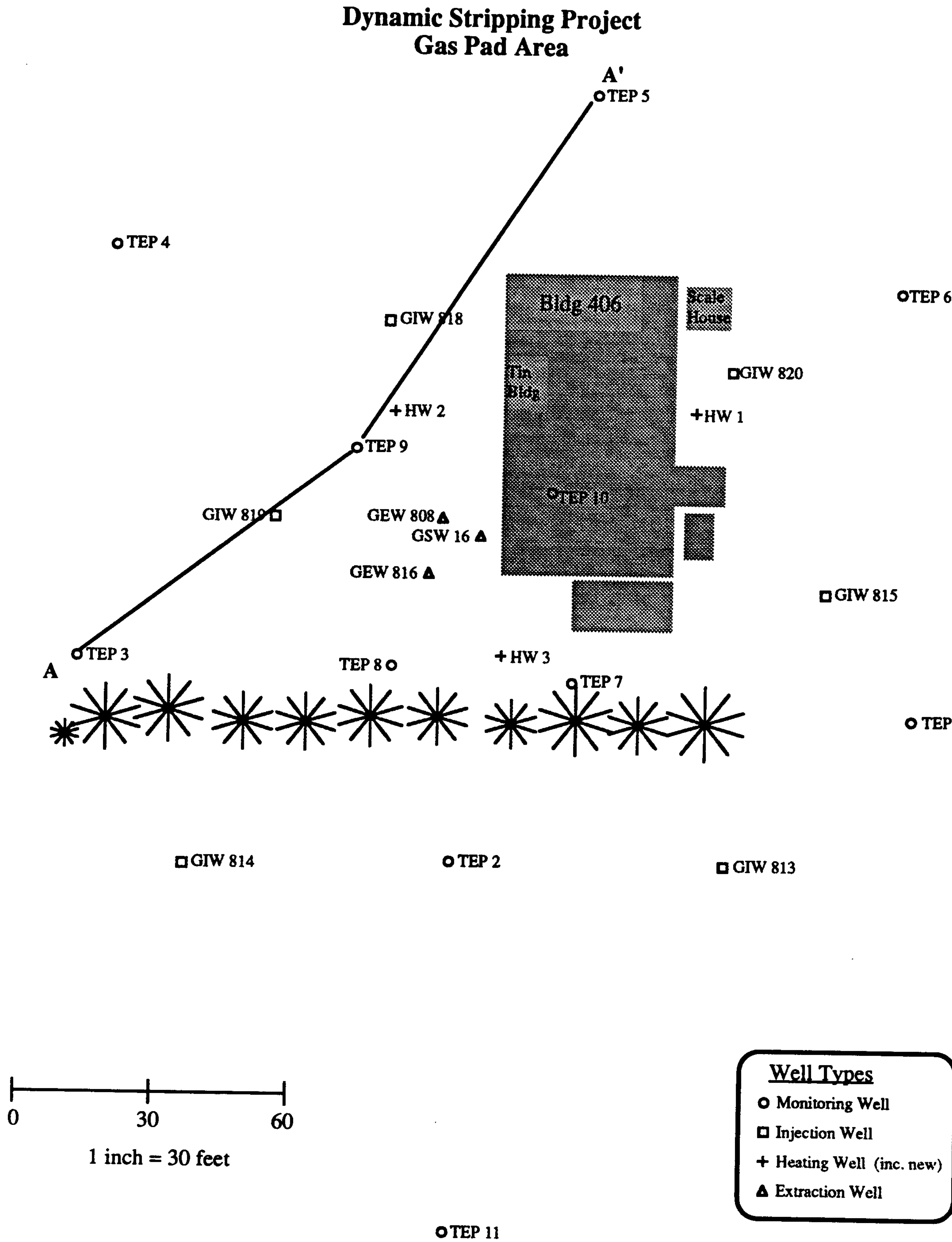

Figure 2. Base map for the LLNL Gasoline Spill Site

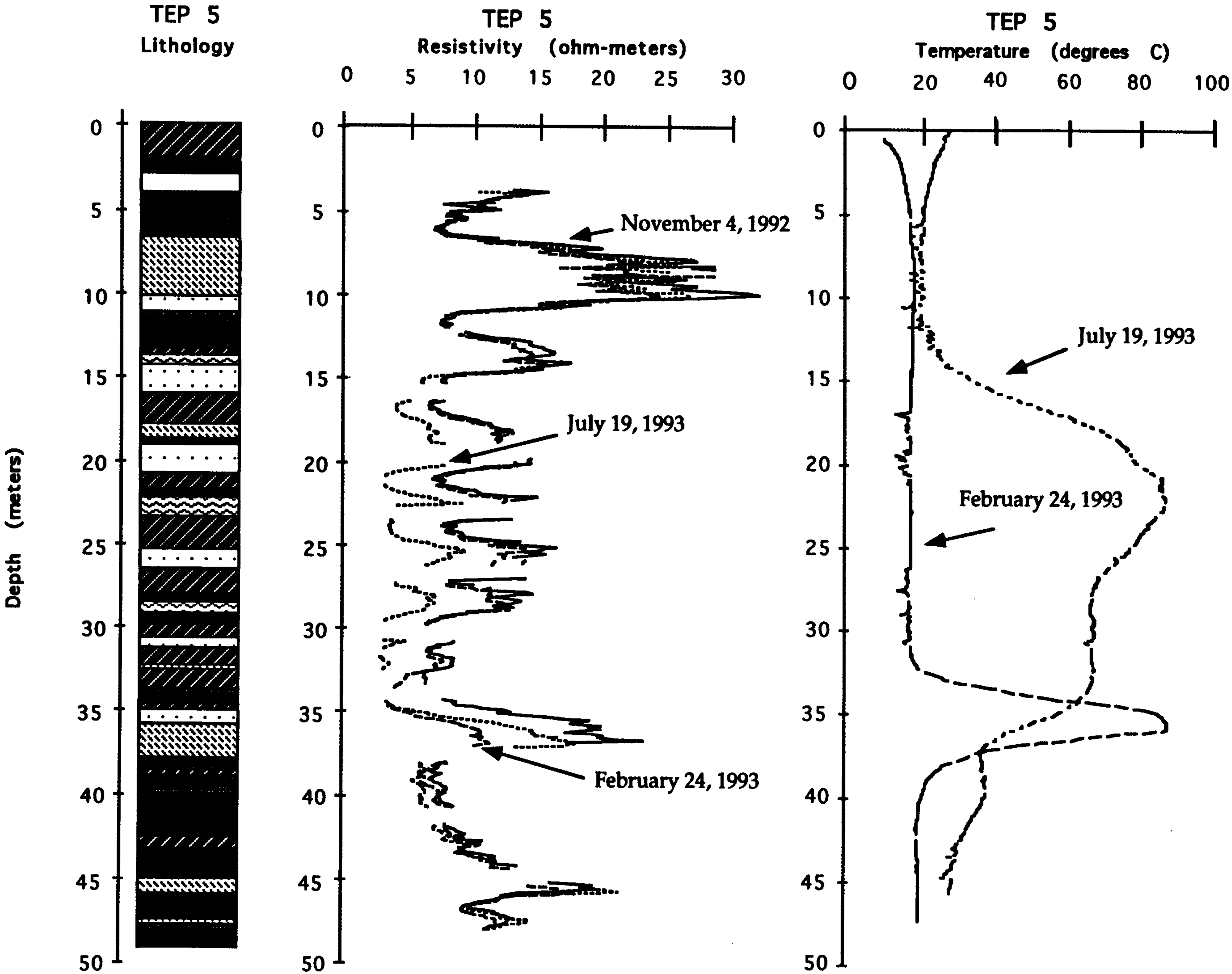

Figure 3. Comparison of lithology, induction and temperature logs for monitoring well TEP 005.

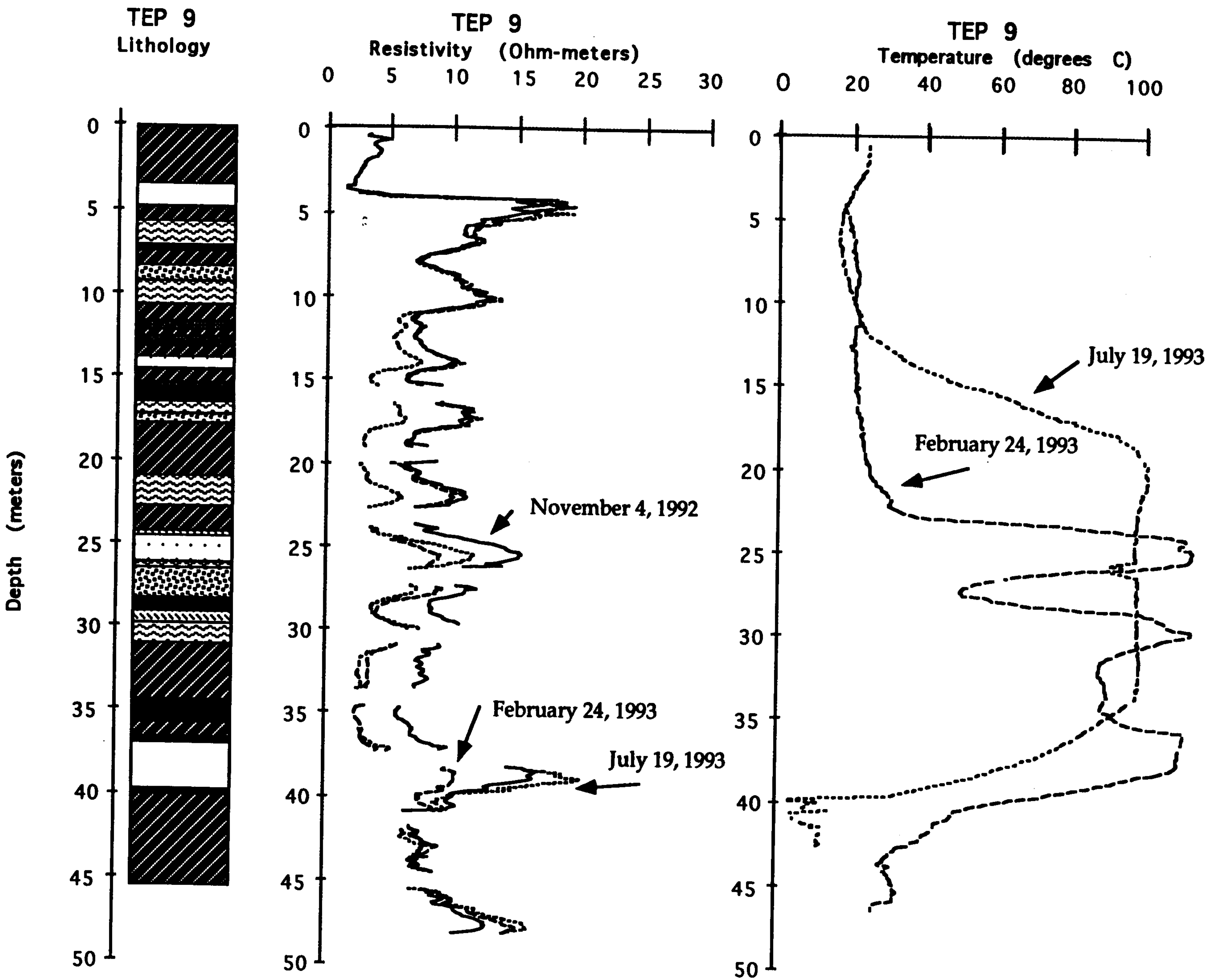

Figure 4. Comparison of lithology, induction and temperature logs in monitoring well TEP 009.

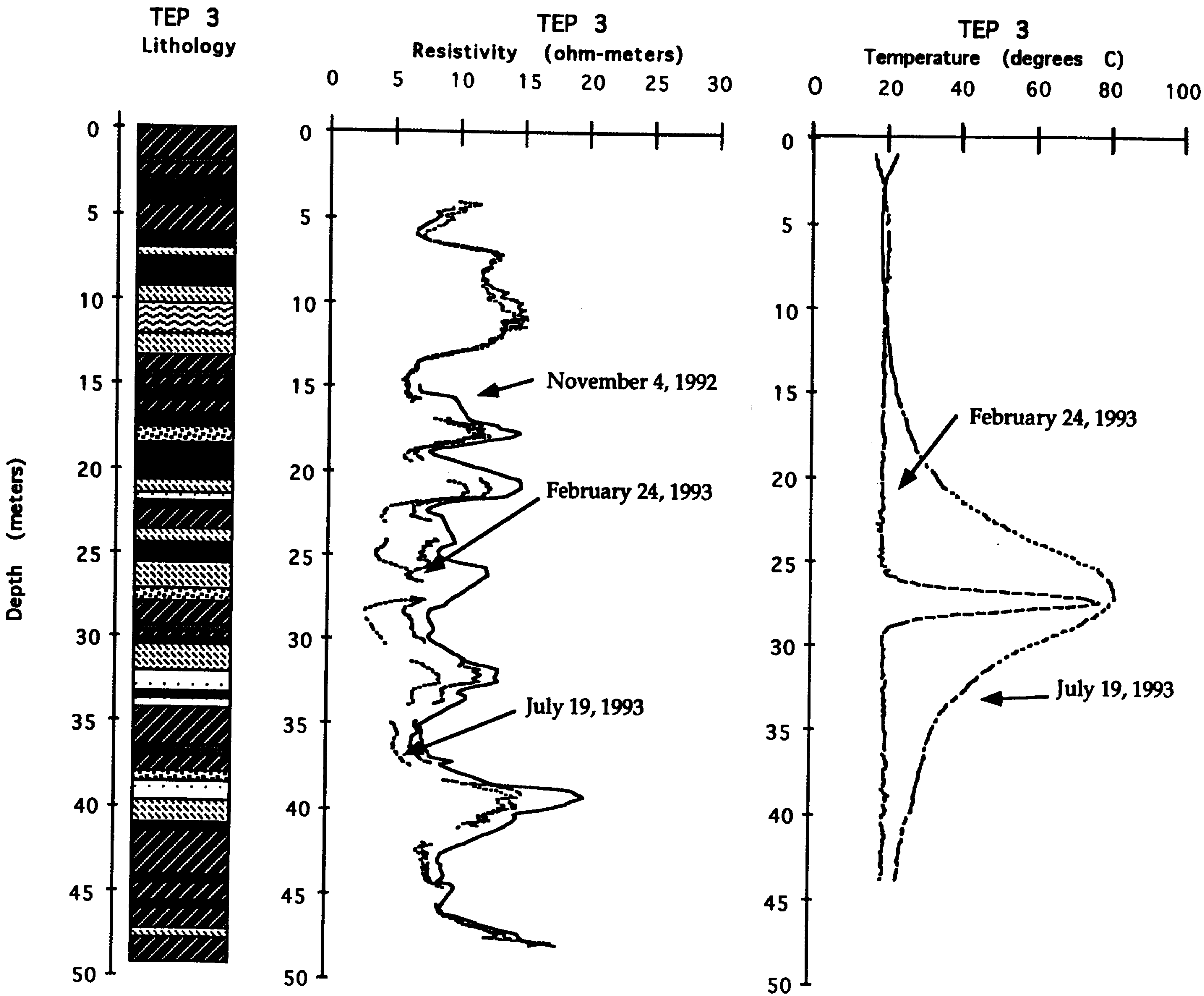

Figure 5. Comparison of lithology, induction and temperature logs in monitoring well TEP 003.

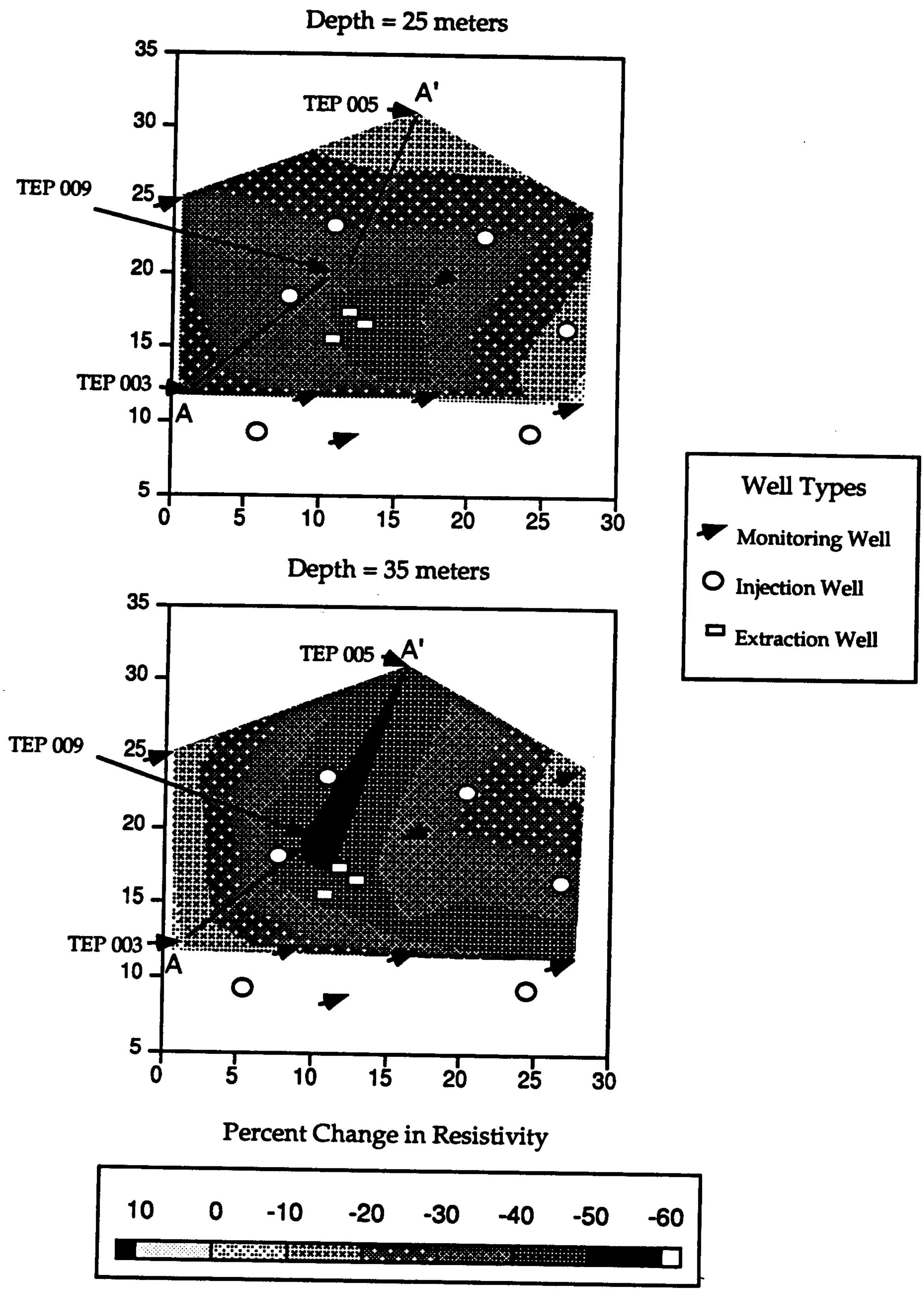

Figure 6. Map view of resistivity changes at depths of 25 and 35 m.
These changes occurred between November 4, 1992 and February 24, 1993.

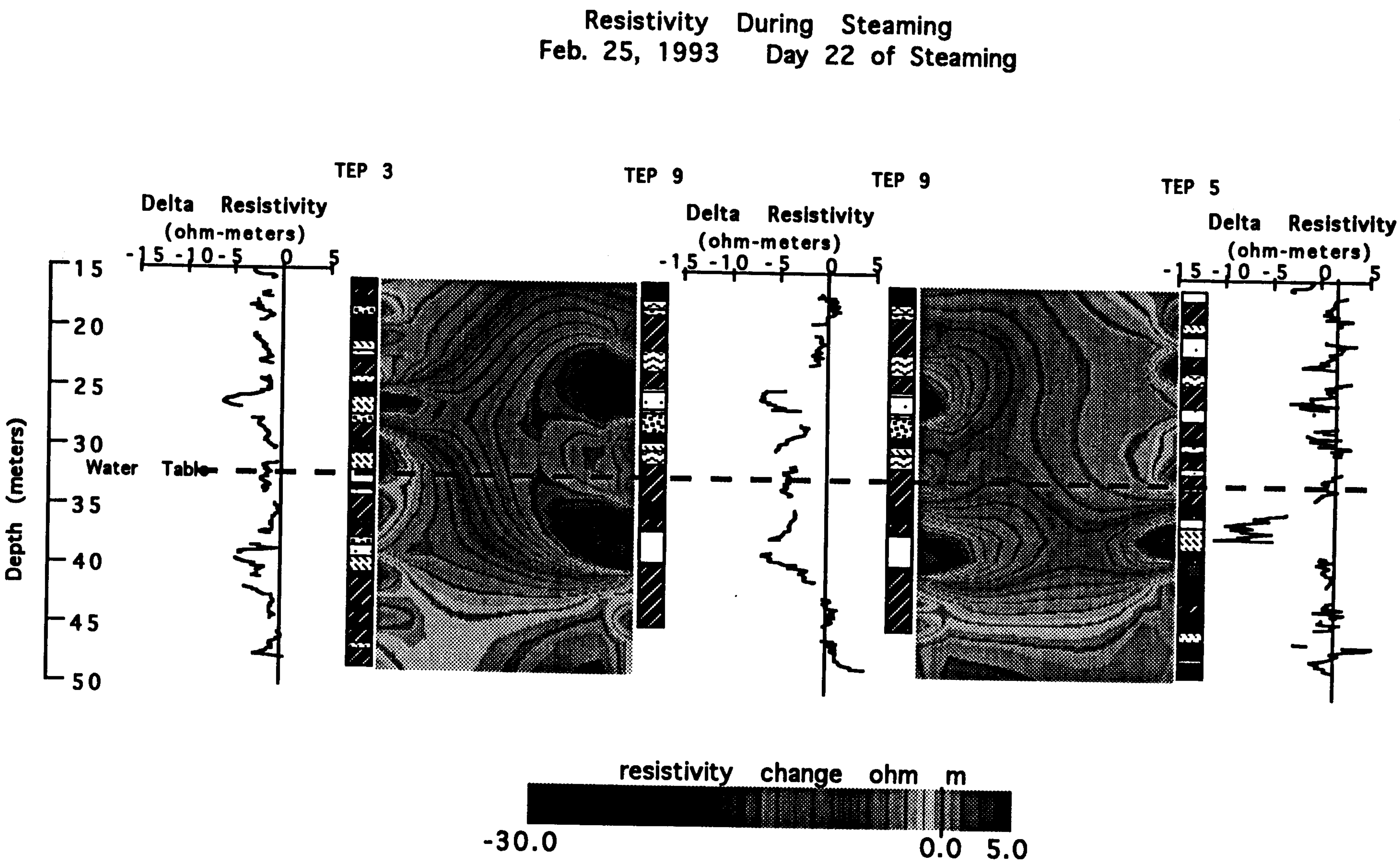

Figure 7. Change in resistivity for induction logs and ERT images from November 1992 to February 25, 1993.